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(54) **Dental surface imaging using polarized fringe projection**

Zahnoberflächenbildgebung unter Anwendung von Schutz polarisierter Ränder

Imagerie de surface dentaire utilisant une protection de frange polarisée

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EP 2 241 247 B1

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Description

FIELD OF THE INVENTION

[0001] The invention relates generally to the field of diagnostic imaging using structured light and more particularly relates to a method for three-dimensional imaging of the surface of teeth and other structures using fringe projection.

BACKGROUND OF THE INVENTION

[0002] Fringe projection imaging uses patterned or structured light to obtain surface contour information for structures of various types. In fringe projection imaging, a pattern of lines of an interference fringe or grating is projected toward the surface of an object from a given direction. The projected pattern from the surface is then viewed from another direction as a contour image, taking advantage of triangulation in order to analyze surface information based on the appearance of contour lines. Phase shifting, in which the projected pattern is incrementally spatially shifted for obtaining additional measurements at the new locations, is typically applied as part of fringe projection imaging, used in order to complete the contour mapping of the surface and to increase overall resolution in the contour image.

[0003] Fringe projection imaging has been used effectively for surface contour imaging of solid, highly opaque objects and has been used for imaging the surface contours for some portions of the human body and for obtaining detailed data about skin structure. However, a number of technical obstacles have prevented effective use of fringe projection imaging of the tooth. One particular challenge with dental surface imaging relates to tooth translucency. Translucent or semi-translucent materials in general are known to be particularly troublesome for fringe projection imaging. Subsurface scattering in translucent structures can reduce the overall signal-to-noise (S/N) ratio and shift the light intensity, causing inaccurate height data. Another problem relates to high levels of reflection for various tooth surfaces. Highly reflective materials, particularly hollowed reflective structures, can effectively reduce the dynamic range of this type of imaging.

[0004] In fringe projection imaging overall, contrast is typically poor, with noise as a significant factor. To improve contrast, many fringe projection imaging systems take measures to reduce the amount of noise in the contour image. In general, for accurate surface geometry measurement using fringe imaging techniques, it is important to obtain the light that is directly reflected from the surface of a structure under test and to reject light that is reflected from material or structures that lie beneath the surface. This is the approach that is generally recommended for 3D surface scanning of translucent objects. A similar approach must be used for intra-oral imaging.

[0005] From an optics perspective, the structure of the tooth itself presents a number of additional challenges for fringe projection imaging. As noted earlier, light penetrating beneath the surface of the tooth tends to undergo significant scattering within the translucent tooth material. Moreover, reflection from opaque features beneath the tooth surface can also occur, adding noise that degrades the sensed signal and thus further complicating the task of tooth surface analysis.

[0006] One corrective measure that has been attempted to make fringe projection workable for contour imaging of the tooth is application of a coating that changes the reflective characteristics of the tooth surface itself. Here, to compensate for problems caused by the relative translucence of the tooth, a number of conventional tooth contour imaging systems apply a paint or reflective powder to the tooth surface prior to surface contour imaging. For the purposes of fringe projection imaging, this added step enhances the opacity of the tooth and eliminates or reduces the scattered light effects noted earlier. However, there are drawbacks to this type of approach. The step of applying a coating powder or liquid adds cost and time to the tooth contour imaging process. Because the thickness of the coating layer is often non-uniform over the entire tooth surface, measurement errors readily result. More importantly, the applied coating, while it facilitates contour imaging, can tend to mask other problems with the tooth and can thus reduce the overall amount of information that can be obtained.

[0007] Even where a coating or other type of surface conditioning of the tooth is used, however, results can be disappointing due to the pronounced contours of the tooth surface. It can be difficult to provide sufficient amounts of light onto, and sense light reflected back from, all of the tooth surfaces. The different surfaces of the tooth can be oriented at 90 degrees relative to each other, making it difficult to direct enough light for accurately imaging all parts of the tooth.

[0008] There have been a number of attempts to adapt structured light surface-profiling techniques to the problems of tooth structure imaging. For example, U.S. Patent No. 5,372,502 entitled "Optical Probe and Method for the Three-Dimensional Surveying of Teeth" to Massen et al. describes the use of an LCD matrix to form patterns of stripes for projection onto the tooth surface. A similar approach is described in U.S. Patent Application Publication 2007/0086762 entitled "Front End for 3-D Imaging Camera" by O'Keefe et al. This document relates to a three-dimensional imaging system for forming a three dimensional image of an object tooth. The system includes a projection unit capable of generating a projected light pattern and a detector unit capable of detecting an image pattern received from the object tooth. An optical transceiver unit transmits the projected pattern generated by the projection unit to the object tooth and receives the image pattern from the object tooth. The optical transceiver is formed of an integrated body having at least first and second transmitting faces and a reflecting surface

that reflects light propagating within the body. The projected pattern light may be polarized in one polarization state and the detected image light may be polarized in a second polarization state orthogonal to the first polarization state. U.S. Patent No. 7,312,924 entitled "Polarizing Multiplexer and Methods for Intra-Oral Scanning" to Trissel describes a method for profiling the tooth surface using triangularization and polarized light, but needing application of a fluorescent coating for operation. Similarly, U.S. Patent No. 6,885,464 entitled "3-D Camera for Recording Surface Structures, In Particular for Dental Purposes" to Pfeiffer et al. discloses a dental imaging apparatus using triangularization but also requiring the application of an opaque powder to the tooth surface for imaging.

[0009] Furthermore, EP 1 1391 176 A1 relates to a method and an arrangement for performing measurements of the topography of an eye surface, wherein projecting means for projecting an image onto said eye surface comprises a projection light source, and wherein at least a fraction of light leaving the surface as a result of said projection is received using one or more receiving units, such as charged coupled device based cameras. The topography of the surface is determined by analysis of said fraction of light leaving the surface, and the image projected onto the surface is projected with light comprising a colour for which the surface is opaque

[0010] It can be appreciated that an apparatus and method that provides accurate surface contour imaging of the tooth, without the need for applying an added coating or other conditioning of the tooth surface for this purpose, would help to speed reconstructive dentistry and could help to lower the inherent costs and inconvenience of conventional methods, such as those for obtaining a cast or other surface profile for a crown, implant, or other restorative structure.

SUMMARY OF THE INVENTION

[0011] It is an object of the present invention to advance the art of diagnostic imaging, particularly for intra-oral imaging applications. With this object in mind, the present invention provides an intra-oral imaging apparatus as set forth in claim 1. Further embodiments of the invention are detailed in the following description and the dependent claims. The intro oral camera may comprise: a fringe pattern generator energizable to emit a fringe pattern illumination having a predetermined spatial frequency, with light in the 350 - 500 nm range; a polarizer in the path of the fringe pattern illumination emitted from the fringe pattern generator and having a first polarization transmission axis; a projection lens disposed to direct the polarized fringe pattern illumination as incident illumination toward a tooth surface; an imaging lens disposed to direct at least a portion of the light reflected and scattered from the incident illumination at the tooth surface along a detection path; an analyzer disposed along the detection path and having a second polarization transmission axis; a detector disposed along the detection path for obtaining image data from the light provided through the analyzer; and a control logic processor responsive to programmed instructions and actuable to obtain image data from the detector and to adjust the intensity over one or more portions of the fringe pattern illumination that is emitted from the fringe pattern generator according to the obtained image data.

[0012] It is a feature of the present invention that it applies light of suitable polarization and wavelength along with fringe projection patterning of varying brightness to the task of tooth contour imaging.

[0013] An advantage offered by the apparatus and method of the present invention relates to improved imaging of tooth surfaces and at lower cost over conventional contour imaging methods. Unlike conventional methods, no powder or other opaque substance must be applied to the tooth as a preparatory step for contour imaging.

[0014] These objects are given only by way of illustrative example, and such objects may be exemplary of one or more embodiments of the invention. Other desirable objectives and advantages inherently achieved by the disclosed invention may occur or become apparent to those skilled in the art. The invention is defined by the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] The foregoing and other objects, features, and advantages of the invention will be apparent from the following more particular description of the embodiments of the invention, as illustrated in the accompanying drawings. The elements of the drawings are not necessarily to scale relative to each other.

FIG. 1 is a schematic diagram of an imaging apparatus using polarized fringe projection imaging in one embodiment.

FIG. 2A is a block diagram showing the use of an analyzer with its polarization axis in parallel to the polarizer of a polarized fringe projection imaging apparatus.

FIG. 2B is a block diagram showing the use of an analyzer with its polarization axis orthogonal to the polarizer of a polarized fringe projection imaging apparatus.

FIG. 3A shows the polarization-dependent reflection and scattering of illumination incident on the tooth.

FIG. 3B is a diagram showing the relative intensities of reflected light and the scattered light from incident illumination.

FIGS. 4A, 4B, and 4C are perspective views of a tooth imaged with fringe projection imaging, using non-polarized light, cross-polarized light, and co-polarized light, respectively.

FIG. 5A is a diagram showing wavelength-dependent penetration of illumination incident on the tooth.

FIG. 5B is a schematic diagram showing relative intensities of reflected and scattered light with different wavelengths.

FIG. 6 is a schematic diagram showing an imaging apparatus for obtaining both co-polarized and cross-polarized light in fringe projection imaging.

FIG. 7 is a block diagram showing components of an intra-oral imaging system according to one embodiment.

FIG. 8 is a schematic diagram showing how increased brightness can be applied for improved imaging over a portion of the imaging field with contoured surfaces.

FIGS. 9A and 9B show exemplary projected light patterns generated for contour imaging in one embodiment.

FIG. 10 is a logic flow diagram that shows the sequence for obtaining a contour-compensated image.

FIG. 11 is a schematic block diagram showing components of a pattern generator in one embodiment.

FIG. 12 is a schematic diagram of an imaging apparatus using polarized fringe projection imaging in one embodiment.

DETAILED DESCRIPTION OF THE INVENTION

[0016] The figures provided herein are given in order to illustrate key principles of operation and component relationships along their respective optical paths according to the present invention and are not drawn with intent to show actual size or scale. Some exaggeration may be necessary in order to emphasize basic structural relationships or principles of operation. Some conventional components that would be needed for implementation of the described embodiments; such as support components used for providing power, for packaging, and for mounting and protecting system optics, for example, are not shown in the drawings in order to simplify description of the invention itself. In the drawings and text that follow, like components are designated with like reference numerals, and similar descriptions concerning components and arrangement or interaction of components already described are omitted.

[0017] In the context of the present disclosure, the term "fringe pattern illumination" is used to describe the type of structured illumination that is used for fringe projection imaging or "contour" imaging. The fringe pattern itself can include, as pattern features, multiple lines, circles, curves, or other geometric shapes that are distributed over the area that is illuminated and that have a predetermined spatial frequency, recurring at a given period.

[0018] Two portions of a line of light or other feature in a pattern of structured illumination can be considered to be substantially "dimensionally uniform" when their line width is the same over the length of the line to within no more than +/- 15 percent. As is described in more detail subsequently, dimensional uniformity of the pattern of structured illumination is needed to maintain a uniform spatial frequency.

[0019] As noted above in the background section, conventional approaches for fringe projection imaging fall short of providing good results for tooth tissue for a number of reasons. Apparatus and methods of the present invention address the problems of obtaining images of the tooth when using fringe projection imaging with fringe pattern illumination by selection of favorable light properties and by techniques that improve light delivery to the highly contoured tooth surface.

[0020] Referring to the schematic block diagram of Figure 1, there is shown an embodiment of an intra-oral imaging apparatus 10 for obtaining surface contour information from a tooth 20 using structured light. A fringe pattern generator 12 is energizable to form the structured light as a fringe pattern illumination and project the structured light thus formed as incident light toward tooth 20 through a polarizer 14 and projection lens 16. Light reflected and scattered from tooth 20 is provided to a detector 30, through an imaging lens 22 and ari analyzer 28. Detector 30 is disposed along a detection path 88, at the image plane of imaging lens 22. A control logic processor 34 accepts feedback information from detector 30 and, in response to this and other data, is actuable to effect the operation of pattern generator 12, as described in more detail subsequently.

[0021] One function of control logic processor 34 for fringe projection imaging is to incrementally shift the position of the fringe and trigger the detector to take images that are then used to calculate three-dimensional information of tooth surface. For the phase shifting fringe projection method, at least three images are typically needed in order to provide enough information for calculating the three-dimensional information of the object. The relative positions of the fringes for these three projected images are typically shifted by one-third of the fringe period. Control logic processor 34 can be a computer, microprocessor, or other dedicated logic processing apparatus that executes programmed instructions.

[0022] Intra-oral imaging apparatus 10 of Figure 1 uses polarized light for surface imaging of tooth 20. Polarizer 14 provides the fringe pattern illumination from fringe pattern generator 12 as linearly polarized light. In one embodiment, the transmission axis of analyzer 28 is parallel to the transmission axis of polarizer 14. With this arrangement, only light with the same polarization as the fringe pattern is provided to the detector 30. In another embodiment, analyzer 28, in the path of reflected light to detector 30, is rotated by an actuator 18 into either of two orientations as needed:

(a) Same polarization transmission axis as polarizer 14. In this "co-polarization" position, detector 30 obtains the specular light reflected from the surface of tooth 20, and most of the light scattered and reflected from the superficial layer of enamel surface of tooth 20, as well as some of the light scattered back from sub-surface portions of the tooth. The co-polariza-

tion orientation of the analyzer 28 axis is shown in Figure 2A. Parallel or co-polarization provides improved contrast over other configurations.

(b) Orthogonal polarization transmission axis relative to polarizer 14. Using the orthogonal polarization, or cross-polarization, helps to reduce the specular component from the tooth surface and obtain more of the scattered light from inner portions of the tooth. The cross-polarization orientation of the analyzer 28 axis is shown in Figure 2B.

[0023] When the tooth is imaged with an imaging system and sensor, the light that is available to the sensor can be (i) light reflected from the tooth top surface; (ii) light scattered or reflected from the near surface volume or portion of the tooth; and (iii) light scattered inside the tooth. In the context of the present disclosure, the "near-surface volume" of the tooth is that portion of the tooth structure that lies within no more than a few hundred μm of the surface.

[0024] It is known that the light reflected from the tooth surface (i), the specular light, maintains the polarization state of the incident light. As the incident light propagates further into the tooth, the light is increasingly depolarized.

[0025] Disadvantageously, some portion of the specular light (i) for a contour pattern may be incident on more highly reflective portions of the tooth surface, even causing some amount of saturation that degrades light detection. In contrast to conventional approaches that use all the light from the tooth, methods of the invention use at least portions of both the specular light (i) and the near-surface reflected light (ii), and avoid the light scattered deep inside the tooth (iii). Applicants have found that the near-surface light (ii), particularly for blue light and shorter wavelengths, is still substantially polarized. Thus, for example, a large portion of the light scattered and reflected from the superficial layer of the tooth enamel also has the same polarization state as the incident light and as the specular light (i).

[0026] Figure 3A shows why the apparatus and method of the present invention use scattered near-surface light from just beneath the surface of the tooth. When a polarized light P0 with small dimension illuminates the tooth, some of the light P1 is reflected from the surface of the tooth in specular fashion and has the same polarization state as the illumination light P0. The other portion of the illumination light P0 goes into the tooth, is subject to scattering and depolarizes. Some of the scattered light P2 escapes the tooth surface near the illumination region and can reach detector 30 (Figure 1).

[0027] Of particular interest, the spatial "footprint" of the scattered light P2, which relates to the dimensions of pattern features of the structured light, such as line thicknesses, shows an increase over the corresponding spatial footprint of reflected light P1. For example, where the structured light pattern consists of parallel lines of light of a given thickness, the reflected light P1 from these pattern features has lines of substantially the same thickness as the projected pattern. However, the scattered light P2 is detected as lines of slightly increased thickness. That is, since light P2 has been scattered inside the tooth, the projected footprint on the tooth surface is broader than that of the specular reflected light, which is the same size as the illumination beam. The graph of Figure 3B shows the difference between the footprint of the light from the tooth surface (P1) and the light from inside the tooth (P2). To reduce the measurement error that can result, the light detected from inside the tooth should be minimized. Applicants have found that polarization provides an effective discriminator for separating the specular light (P1) from the tooth surface from the scattered light from inside the tooth, while still taking advantage of a portion of the scattered light (P2).

[0028] The group of contour images shown in Figures 4A-4C gives a comparison of approaches for obtaining and using light returned from the tooth using fringe projection. Figure 4A shows a contour image of tooth 20 obtained using unpolarized light. Figure 4B shows a somewhat poorer image using cross-polarized light, but not exhibiting specular reflection. Figure 4C shows the improvement in the image contrast when using co-polarized light. Areas of high brightness in this image are due to specular reflection. As these images show, fringe contrast improves when the cross-polarization light is blocked from the image detector.

[0029] In addition to taking advantage of favorable properties of polarized light, embodiments of the present invention also take advantage of different amounts of reflection that correspond to the wavelength of light directed toward the tooth. Figure 5A shows three different wavelengths λ1, λ2, and λ3 as directed toward tooth 20. The shortest wavelength at λ1 penetrates the tooth the shortest distance. The next longest wavelength at λ2 penetrates the tooth an additional distance. Finally, the longest wavelength at λ3 penetrates the tooth the farthest distance. The graph of Figure 5B shows how scattering affects the footprint of the light on the tooth surface from each wavelength. The longer the wavelength, the larger the footprint, resulting in larger measurement error. Wavelength λ1 could be near-UV or blue light in the range of 350 to 500 nm, for example. Wavelength λ2 could be green light in the range of 500 to 700 nm, for example. Wavelength λ3 could be red or IR light in the range of 700nm or higher, for example. Thus, blue or near UV light in the approximate 350 - 500 nm range, because it provides the least penetration into the tooth structure, proves to be a suitable light source for fringe projection imaging in one embodiment.

[0030] For the embodiment of Figure 1, spatial light modulators can be used as part of fringe pattern generator 12 to provide the needed shifting motion for polarized fringe projection imaging, as described in more detail subsequently. The fringe pattern itself is shifted to at least one alternate position during imaging, more preferably to two or more alternate positions. This shifting of the light pattern can be caused by a separate actuator (not

shown in Figure 1), such as a piezoelectric or other type of actuator that is part of fringe pattern generator 12 for achieving precision incremental movement. Alternately, where fringe pattern generator 12 uses a spatial light modulator, this shifting can be performed electronically, without mechanical movement of parts within fringe pattern generator 12. In addition, another actuator 18 can be positioned for providing 90 degree rotation to either polarizer 14 or analyzer 28 (such as is shown in Figure 1) in order to obtain both co-polarization and cross-polarization images. Polarization can also be rotated when using an LCD spatial light modulator.

[0031] Figure 6 shows an embodiment of an intra-oral imaging apparatus 40 that obtains images using both parallel and cross-polarization without requiring rotation of either polarizer 14 or analyzer 28 between image captures. A polarization beam splitter 36 separates the reflected and scattered light, reflecting the cross-polarized light to a detector 30b and transmitting the co-polarized light to a detector 30a.

[0032] Because the co-polarized and cross-polarized light provide different types of information about the surface and near-surface of the tooth, imaging apparatus 40 of Figure 6 offers the advantage of using both polarizations without the need for mechanical movement of analyzer 28 or polarizer 14, combining the results from orthogonal polarizations in order to obtain improved surface contour data.

[0033] Detectors 30, 30a, or 30b in the embodiments described herein can be any of a number of types of image sensing array, such as a CCD device, for example. Polarizers and analyzers can be wire-grid or other polarizer types.

[0034] In one embodiment of the present invention, the imaging apparatus is packaged in the form of a handheld probe that can be easily positioned within the patient's mouth with little or no discomfort. Referring to Figure 7, there is shown an intra-oral imaging system 42 that includes imaging apparatus 10 in the form of a probe. The probe communicates, over a wired or wireless data communication channel, with control logic processor 34 that obtains the images from either or both co-polarized and cross-polarized projection fringes. Control logic processor 34 provides output image data that can be stored as a data file and displayed on a display 38.

[0035] As noted in the background section, the pronounced contours of the tooth include surfaces that are steeply sloped with respect to each other, complicating the task of directing enough light onto each surfaces As a result, some surfaces of the tooth may not provide 3-D information that is sufficient. Referring to Figure 8, this problem is represented relative to a rear surface 26 of tooth 20. Patterned light from imaging apparatus 10 generates a contour-detecting fringe pattern 44 onto tooth 20, as shown in box B. Fringe pattern 44 is sufficiently bright for obtaining 3-D image content over a top surface area, as outlined over an area 52; however, the back surface area corresponding to rear surface 26 of tooth 20 and outlined as a darker area 54 is very dimly lit. This allows only a coarse estimation, at best, of the contour of rear surface 26.

[0036] In order to compensate for this lack of brightness using conventional fringe projection patterning techniques, an embodiment of the present invention selectively increases the light intensity of the fringe pattern illumination over a given area. In Figure 8, a fringe pattern 50 is shown with two different areas, differentiated by their relative light intensities. In fringe pattern 50, a first intensity 56 is provided for fringe projection imaging of surfaces such as top surface area that are more readily accessible for contour imaging. A second intensity 58, higher than first intensity 56 for the example shown and as indicated by darker lines in Figure 8, is provided for the back surface area of the tooth. It should be observed that the actual pattern feature spacing and thickness of the projected contour lines that are the pattern features in this example is not changed in this embodiment. The same spatial frequency of fringe pattern 50 is preserved. This means that the contour pattern, fringe pattern 50, remains dimensionally uniform, with individual lines or other pattern features changed only in intensity, rather than in dimension or spacing (period). Only the relative intensity of the fringe pattern illumination over one or more areas is increased where needed. For example, along any one line within structured light fringe pattern 50, there can be any number of intensities, such as the two shown as first and second intensities 56 and 58 in Figure 8. The line thickness within the fringe pattern does not change; the spatial frequency of the fringe pattern is preserved.

[0037] Maintaining dimensional uniformity and spatial frequency of the fringe pattern is advantageous for contour imaging because it provides a uniform resolution over the full image field. Other techniques have been proposed for changing the pattern dimensions itself, such as thickening the pattern lines over specific areas; however, because the spatial frequency of the fringe pattern changes when using such a technique, the resulting resolution of the contour image that is obtained is non-uniform. With respect to the example fringe pattern 50 given in Figure 8, it is instructive to observe that if the area indicated as second intensity 58 actually used thicker lines, the resulting contour image would suffer reduced resolution over this area. By maintaining the lines of fringe pattern 50 as dimensionally uniform and only increasing the intensity of light to provide second intensity 58 in this example, embodiments of the present invention provide an increased illumination without loss of resolution over the darker region.

[0038] The schematic diagram of Figure 8 showed a simple case in which fringe pattern 50 compensates for surface steepness by using two different intensities 56 and 58. Figures 9A and 9B show examples of other possible arrangements that use more than two light intensities. In Figure 9A, for example, light for the fringe pattern illumination can be of first intensity 56, second intensity

58, or a third intensity 66, represented as the highest intensity in this example. In Figure 9B, light can be of first, second, or third intensities 56, 58, or 66 respectively, or of an even higher fourth intensity 68 as shown. The light intensity can vary along any individual pattern feature, such as along a single line in the projected fringe pattern 50.

[0039] In addition to increasing the light intensity over darker areas of the tooth surface relative to the position of imaging apparatus 10, it is also possible to reduce the light intensity over areas where there may be highly specular reflection that otherwise causes saturation of the detector. Again, it must be emphasized that what changes is the light intensity over one or more portions of the projected light pattern; line thickness and spacing, both related to the spatial frequency, remain the same for different intensities.

[0040] Referring again to Figures 1 and/or 6, the light intensity over the projected pattern can be changed by controlling fringe pattern generator 12 by means of commands from control logic processor 34, in response to programmed instructions, and by means of signals provided from control logic processor 34 to related control components. In one embodiment, fringe pattern generator 12 is a digital micromirror device (DMD). Intensity can then be increased over any portion of projected fringe pattern 50 by increasing the effective duty cycle of the rotatable mirrors of the DMD using Pulse-Width Modulation (PWM), so that the source illumination is provided for a suitable amount of time over a particular portion of the fringe pattern. Other methods of illumination intensity adjustment would apply for LCD and for other transmissive and missive spatial light modulators, using light modulation techniques familiar to those skilled in the imaging arts.

[0041] Referring again to Figure 7, control logic processor 34 is programmed with instructions that automatically adapt the local intensities of lines or other features in fringe pattern 50 according to imaging conditions.

[0042] The logic flow diagram of Figure 10 shows a sequence of steps that are used for adaptive fringe projection imaging in one embodiment. In an initial step 60 a first reference image is obtained. The reference image can be a contour image, formed by projecting structured light onto the tooth surface. Alternately, the reference image can be a conventional two-dimensional image obtained from projection of a uniform field of light onto the tooth surface. The reference image that is obtained can be at full resolution; alternately, since the reference image is not used directly for imaging but instead to determine the overall amount of light that is returned over each surface area, the reference image can be at lower resolution.

[0043] Still referring to Figure 10, an analysis step 64 follows, in which areas from the sensed reference image that are not sufficiently bright are identified. For dental imaging applications, analysis step 64 can take advantage of known data about tooth structure. The operator, for example, may identify the tooth by number or provide other information that is used in analysis step 64. A map generation step 70 is then executed, in which areas of greater or lesser intensity are defined according to the first reference image. With respect to Figures 9A and 9B, step 70 then sets up variable intensity fringe pattern 50. An image acquisition step 74 then uses the generated fringe pattern 50 for obtaining a contour image with added brightness as described with respect to Figure 8. Image acquisition step 74 may be followed by an optional looping step 76 that repeats the analysis of map generation step 70 in order to generate a second or other additional mappings so that the projected structured illumination pattern can be shifted, with appropriate changes in intensity, one or more times. This shifting is done in order to.obtain a more accurate evaluation of tooth contour using fringe projection techniques. The individually obtained contour images are combined to obtain surface structure information, using techniques well known in the imaging arts. In one embodiment, image acquisition step 74 also includes energizing actuator 18 (Figure 1) in order to obtain images using both co-polarization (as in Figure 2A) and cross-polarization (Figure 2B).

[0044] Figure 11 is a schematic block diagram showing components of fringe pattern generator 12 in one embodiment. A spatial light modulator 84, such as a digital micromirror device (DMD), liquid crystal device (LCD), or other type of light modulator array or grating forms a pattern according to control signals from control logic processor 34. A light source 80 provides incident light to spatial light modulator 84, conditioned by one or more optical elements 82, such as a light uniformizer and lens elements. Spatial light modulator 84 in this embodiment may be a transmissive device as shown in Figure 11 or a reflective device, such as a DMD. Control logic processor 34 responds to pattern 44 of light brightness that is returned in the initial reference image as was described earlier with reference to Figure 8 to control the intensity of pattern features in the fringe pattern that it forms on spatial light modulator 84.

[0045] In the embodiment shown in Figure 11, light source 80 can be a solid-state light source, such as a Light-Emitting Diode (LED) or laser, or can be a lamp or other light source. Blue or near UV light in the 350 - 500 nm range is used for providing usable image content from near-surface portions of the tooth, as described earlier. In an alternate embodiment, light source 80 is not used and an emissive array, such as an Organic LED (OLED) is used for pattern generation from a single components.

[0046] The schematic diagram of Figure 12 shows another embodiment of the present invention wherein a filter 90, such as a bandpass filter that transmits blue or near UV light in the 350 - 500 nm range and attenuates other light, is placed in the imaging path. This embodiment can be less sensitive to factors in the environment, such as stray light from other equipment in the room. In this embodiment, light source 80 within fringe pattern generator 12 (Figure 11) can be either broadband, extending well

beyond the 350-500 nm range, or narrow-band, primarily emitting blue and near-UV light.

[0047] Embodiments of the present invention provide improved contour imaging for teeth by taking advantage of properties of light and capabilities of spatial light modulators for forming an adaptive fringe projection pattern having suitable light intensity that is responsive to variability in tooth surface characteristics. The apparatus and methods of the present invention compensate for problems related to the translucence of the tooth by using short-wavelength light and by employing principles of polarized light. When light of suitable wavelength and polarization state is provided with an adaptable intensity arrangement, a more accurate indicator of the highly contoured tooth surface can be achieved.

[0048] The surface contour image that is obtained using the apparatus and methods of the present invention can be used in a number of ways. Contour data can be input into a system for processing and generating a restorative structure or can be used to verify the work of a lab technician or other fabricator of a dental appliance. This method can be used as part of a system or procedure that reduces or eliminates the need for obtaining impressions under some conditions, reducing the overall expense of dental care. Thus, the imaging performed using this method and apparatus can help to achieve superior fitting prosthetic devices that need little or no adjustment or fitting by the dentist. From another aspect, the apparatus and method of the present invention can be used for long-term tracking of tooth, support structure, and bite conditions, helping to diagnose and prevent more serious health problems. Overall, the data generated using this system can be used to help improve communication between patient and dentist and between the dentist, staff, and lab facilities.

[0049] Advantageously, the apparatus and method of the present invention provide an intra-oral imaging system for 3-D imaging of teeth and other dental features without requiring the use of a special powder or application of some other temporary coating for the tooth surface. The system offers high resolution, in the 25-50 μm range in one embodiment.

[0050] The invention has been described in detail with particular reference to a presently preferred embodiment, but it will be understood that variations and modifications can be effected within the scope of the invention. For example, any of a number of different types of spatial light modulator could be used as part of the fringe pattern generator. The presently disclosed embodiments are therefore considered in all respects to be illustrative and not restrictive. The scope of the invention is indicated by the appended claims, and all changes that come within the meaning and range of equivalents thereof are intended to be embraced therein.

PARTS LIST

[0051]

10.	Imaging apparatus
12.	Fringe pattern generator
14	Polarizer
16.	Lens
18.	Actuator
20.	Tooth
22.	Lens
26.	Rear surface
28.	Analyzer
30, 30a, 30b.	Detector
34.	Control logic processor
36.	Polarization beam splitter
38.	Display
40.	Imaging apparatus
42.	Intra-oral imaging system
44.	Pattern
50.	Fringe pattern
52, 54.	Area
56.	First intensity
58.	Second intensity
60.	Initial step
64.	Analysis step
66.	Third intensity
68.	Fourth intensity
70.	Map generation step
74.	Image acquisition step
76.	Looping step
80.	Light source
82.	Optical element
84.	Spatial light modulator
88.	Detection path
90.	Filter
B.	Box
P0, P1, P2..	Polarized light
λ1, λ2,λ3.	Wavelength

Claims

1. An intra-oral imaging apparatus comprising:

a fringe pattern generator energizable to emit a fringe pattern illumination having a predetermined spatial frequency, using emitted light in a blue light or shorter wave lengths range;

a polarizer disposed in the path of the fringe pattern illumination emitted from the fringe pattern generator and having a first polarization transmission axis;

a projection lens disposed to direct the polarized fringe pattern illumination as incident illumination toward a tooth surface;

an imaging lens disposed to direct at least a portion of the light reflected and scattered from the incident illumination at the tooth surface along a detection path;

an analyzer disposed along the detection path and having a second polarization transmission

axis to provide co-polarization with the polarizer;
a detector disposed along the detection path for obtaining image data from the light provided through the analyzer; and
a control logic processor responsive to programmed instructions and actuable to obtain image data from the detector and according to the obtained image data, selectively to adjust the intensity of the fringe pattern illumination over different areas of the fringe pattern incident on the tooth surface, thereby providing sufficiently bright fringe patterns in such different areas for obtaining image date.

2. The imaging apparatus of claim 1, wherein the second polarization transmission axis is parallel to the first polarization transmission axis.

3. The imaging apparatus of claim 1 or 2, further comprising an actuator coupled to either the polarizer or the analyzer and energizable to rotate the coupled polarizer or analyzer to one of two positions, substantially 90 degrees apart.

4. The imaging apparatus of any one of claims 1 to 3, wherein the analyzer is a polarization beam splitter and wherein the detector is a first detector disposed to receive co-polarized light transmitted through the polarization beam splitter and further comprising a second detector disposed to receive cross polarized light reflected from the polarization beam splitter.

5. The imaging apparatus of any one of the preceding claims, wherein the fringe pattern generator comprises a grating.

6. The imaging apparatus of any one of the preceding claims, wherein the fringe pattern generator comprises a spatial light modulator for shifting the fringe pattern to at least one alternate position on the tooth surface.

7. The imaging apparatus of claim 6, wherein the spatial light modulator is taken from the group consisting of a digital micromirror device and a liquid crystal device.

8. The imaging apparatus of claim 1, wherein the fringe pattern generator comprises an emissive device that forms and emits the fringe pattern.

9. The imaging apparatus of any one of the preceding claims, further comprising a filter disposed along the detection path for transmitting light in the 350 - 500 nm range.

10. The imaging apparatus of any one of the preceding claims, wherein the emitted light is in the range of 350 to 500nm.

11. The imaging apparatus of any one of the preceding claims, wherein the fringe pattern generator comprises a spatial light modulator, the fringe pattern illumination has a plurality of pattern features and wherein the control logic processor is capable of adjusting the intensity of the fringe pattern illumination over one or more of the pattern features, said imaging apparatus further comprising:

a filter disposed along the detection path for transmitting light in the blue light and shorter wavelength and attenuating light outside the range.

12. The imaging apparatus of claim 11, wherein the light transmitted by the filter is in a range of 350 to 500 nm.

Patentansprüche

1. Eine intra-orale Bildgebungsvorrichtung, die Folgendes aufweist:

einen Rand- oder Fringemustergenerator, der ansteuerbar ist um eine Rand- oder Fringemusterbeleuchtung zu emittieren, die eine vorbestimmte Raumfrequenz aufweist, wobei der Generator emittiertes Licht verwendet im Bereich von blauem Licht oder Licht mit einer kürzeren Wellenlänge;
einen Polarisator, der in dem Pfad der Randmusterbeleuchtung angeordnet ist, die von dem Randmustergenerator emittiert wird und der eine erste Polarisationstransmissionsachse aufweist;
eine Projektionslinse, die so angeordnet ist, dass sie die polarisierte Randmusterbeleuchtung als direkte Beleuchtung auf eine Zahnoberfläche lenkt;
eine Abbildungslinse, die so angeordnet ist, dass sie wenigstens einen Teil des reflektierten und gestreuten Lichts von der direkten Beleuchtung an der Zahnoberfläche entlang eines Detektionspfades lenkt;
einen Analysator, der entlang des Detektionspfades angeordnet ist, wobei der Analysator eine zweite Polarisationstransmissionsachse aufweist, um eine Co-Polarisation mit dem Polarisator bereitzustellen;
einen Detektor, der entlang des Detektionspfades angeordnet ist, um Bilddaten von dem Licht, das durch den Analysator bereitgestellt wird, zu erhalten;
einen Steuerlogikprozessor, der ansprechend auf programmierte Anweisungen ist und betätigbar ist, um Bilddaten von dem Detektor zu er-

halten und entsprechend der erhaltenen Bilddaten selektiv die Intensität der Randmusterbeleuchtung über verschiedene Bereiche des auf die Zahnoberfläche auftreffenden Randmusters anpasst, wobei der Prozessor dabei genügend helle Randmuster in unterschiedlichen Bereichen bereitstellt, um Bilddaten zu erhalten.

2. Die Bildgebungsvorrichtung nach Anspruch 1, wobei die zweite Polarisationstransmissionsachse parallel zu der ersten Polarisationstransmissionsachse ist.

3. Die Bildgebungsvorrichtung nach Anspruch 1 oder 2, wobei die Vorrichtung ferner einen Betätiger aufweist, der entweder mit dem Polarisator oder dem Analysator verbunden ist und ansteuerbar ist, so dass der verbundene Polarisator oder der Analysator in eine von zwei Positionen gedreht wird, die im Wesentlichen 90 Grad zueinander stehen.

4. Die Bildgebungsvorrichtung nach einem der Ansprüche 1 bis 3, wobei der Analysator ein Polarisationsstrahlteiler ist und wobei der Detektor ein erster Detektor ist, der so angeordnet ist, dass er co-polarisiertes Licht, das durch den Polarisationsstrahlteiler transmittiert wird, empfängt und wobei die Vorrichtung ferner einen zweiten Detektor aufweist, der so angeordnet ist, dass er kreuzpolarisiertes Licht empfängt, das von dem Polarisationsstrahlteiler reflektiert wird.

5. Die Bildgebungsvorrichtung nach einem der vorhergehenden Ansprüche, wobei der Randmustergenerator ein Beugungsgitter aufweist.

6. Die Bildgebungsvorrichtung nach einem der vorhergehenden Ansprüche, wobei der Randmustergenerator einen Raumlichtmodulator aufweist zum Verschieben des Randmusters an wenigstens eine andere Position auf der Zahnoberfläche.

7. Die Bildgebungsvorrichtung nach Anspruch 6, wobei der Raumlichtmodulator aus der Gruppe bestehend aus einer digitalen Mikrospiegelvorrichtung und einer Flüssigkristallvorrichtung ausgewählt wird.

8. Die Bildgebungsvorrichtung nach Anspruch 1, wobei der Randmustergenerator eine Emissionsvorrichtung aufweist, die das Randmuster bildet und emittiert.

9. Die Bildgebungsvorrichtung nach einem der vorhergehenden Ansprüche, wobei die Vorrichtung ferner einen Filter aufweist, der entlang des Detektionspfades angeordnet ist, zum Transmittieren von Licht im Bereich von 350-500 nm.

10. Die Bildgebungsvorrichtung nach einem der vorhergehenden Ansprüche, wobei das emittierte Licht im Bereich von 350 bis 500 nm liegt.

11. Die Bildgebungsvorrichtung nach einem der vorhergehenden Ansprüche, wobei der Randmustergenerator einen Raumlichtmodulator aufweist, wobei die Randmusterbeleuchtung eine Vielzahl von Mustermerkmalen aufweist und wobei der Steuerlogikprozessor geeignet ist die Intensität der Randmusterbeleuchtung über eines oder mehrere der Mustermerkmale anzupassen, wobei die Bildgebungsvorrichtung ferner Folgendes aufweist:

einen Filter, der entlang des Detektionspfades angeordnet ist, um Licht im Bereich von blauem Licht oder Licht kürzerer Wellenlänge zu transmittieren und Licht außerhalb dieses Bereichs zu dämpfen.

12. Die Bildgebungsvorrichtung nach Anspruch 11, wobei das Licht, das von dem Filter transmittiert wird in einem Bereich von 350 bis 500 nm liegt.

Revendications

1. Dispositif d'imagerie intra-oral comprenant :

un générateur de motif de franges excitable pour émettre un éclairage à motif de franges ayant une fréquence spatiale prédéterminée, utilisant de la lumière émise dans la plage des longueurs d'onde de la lumière bleue ou plus courtes ;
un polariseur disposé dans le chemin de l'éclairage à motif de franges émis par le générateur de motif de franges et ayant un premier axe de transmission de polarisation ;
une lentille de projection disposée de façon à diriger l'éclairage à motif de franges polarisé en tant qu'éclairage incident vers une surface d'une dent ;
une lentille d'imagerie disposée de façon à diriger au moins une partie de la lumière réfléchie et diffusée par l'éclairage incident sur la surface de la dent sur un chemin de détection ;
un analyseur disposé le long du chemin de détection et ayant un deuxième axe de transmission de polarisation pour assurer une co-polarisation avec le polariseur ;
un détecteur disposé sur le chemin de détection pour obtenir des données d'image à partir de la lumière fournie par l'intermédiaire de l'analyseur ; et
un processeur logique de commande agissant en réponse à des instructions programmées et actionnable pour obtenir des données d'image à partir du détecteur et, en fonction des données d'image obtenues, pour ajuster sélectivement

l'intensité de l'éclairage à motif de franges sur différentes zones du motif de franges incident sur la surface de la dent, fournissant ainsi des motifs de franges suffisamment lumineux dans de telles zones différentes pour obtenir des données d'image.

2. Dispositif d'imagerie selon la revendication 1, dans lequel le deuxième axe de transmission de polarisation est parallèle au premier axe de transmission de polarisation.

3. Appareil d'imagerie selon la revendication 1 ou 2, comprenant en outre un actionneur couplé au polariseur ou à l'analyseur et excitable pour faire tourner le polariseur ou l'analyseur couplé dans l'une de deux positions, séparées d'environ 90°.

4. Appareil d'imagerie selon l'une quelconque des revendications 1 à 3, dans lequel l'analyseur est un séparateur de faisceau à polarisation et dans lequel le détecteur est un premier détecteur disposé de façon à recevoir de la lumière co-polarisée transmise par l'intermédiaire du séparateur de faisceau à polarisation et comprenant en outre un deuxième détecteur disposé de façon à recevoir de la lumière à polarisation croisée réfléchie par le séparateur de faisceau à polarisation.

5. Appareil d'imagerie selon l'une quelconque des revendications précédentes, dans lequel le générateur de motif de franges comprend une grille.

6. Appareil d'imagerie selon l'une quelconque des revendications précédentes, dans lequel le générateur de motif de franges comprend un modulateur de lumière spatial pour décaler le motif de franges vers au moins une position alternative sur la surface de la dent.

7. Appareil d'imagerie selon la revendication 6, dans lequel le modulateur de lumière spatial est choisi dans le groupe comprenant un dispositif à micro-miroir numérique et un dispositif à cristaux liquides.

8. Appareil d'imagerie selon la revendication 1, dans lequel le générateur de motif de franges comprend un dispositif émetteur qui forme et émet le motif de franges.

9. Appareil d'imagerie selon l'une quelconque des revendications précédentes, comprenant en outre un filtre disposé dans le chemin de détection pour transmettre de la lumière dans la plage de 350 à 500 nm.

10. Appareil d'imagerie selon l'une quelconque des revendications précédentes, dans lequel la lumière émise est dans la plage de 350 à 500 nm.

11. Appareil d'imagerie selon l'une quelconque des revendications précédentes, dans lequel le générateur de motif de franges comprend un modulateur de lumière spatial, l'éclairage à motif de franges a une pluralité de caractéristiques de motif et dans lequel le processeur logique de commande peut ajuster l'intensité de l'éclairage à motif de franges sur une ou plusieurs des caractéristiques de motif, le dispositif d'imagerie comprenant en outre :

un filtre disposé dans le chemin de détection pour transmettre la lumière dans la plage des longueurs d'onde de la lumière bleue ou plus courtes, et atténuer la lumière en dehors de la plage.

12. Appareil d'imagerie selon la revendication 11, dans lequel la lumière transmise par le filtre est dans une plage de 350 à 500 nm.

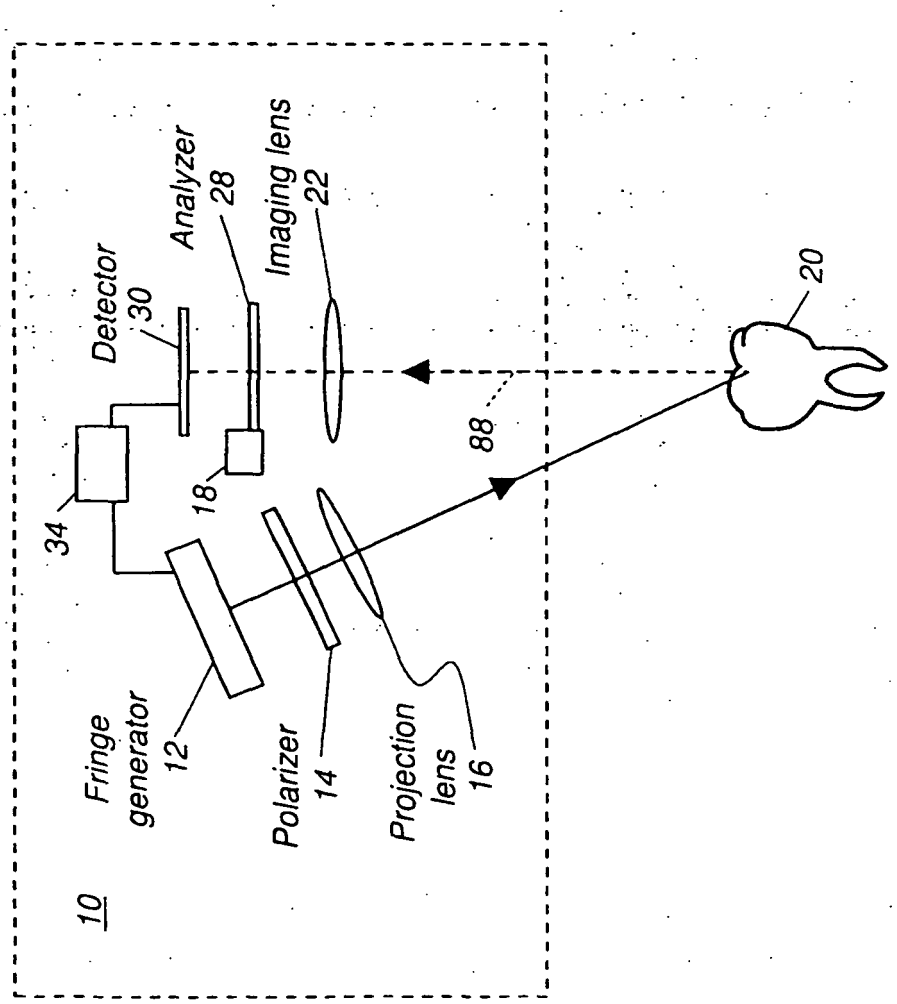

10
Fringe generator 12
Polarizer 14
Projection lens 16
18
34
Detector 30
Analyzer 28
Imaging lens 22
88
20

FIG. 1

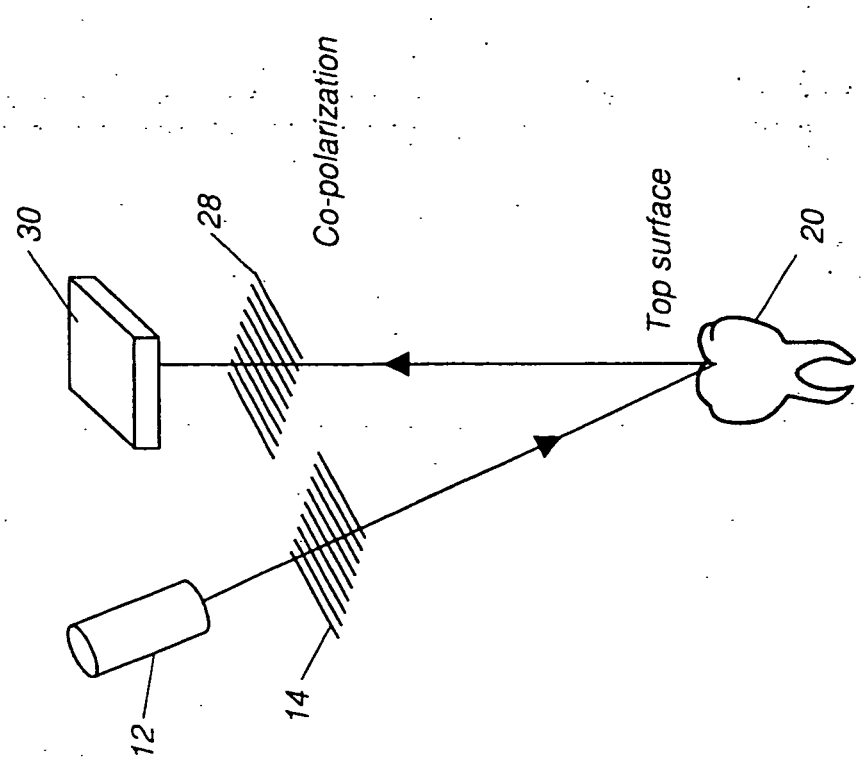


FIG. 2A

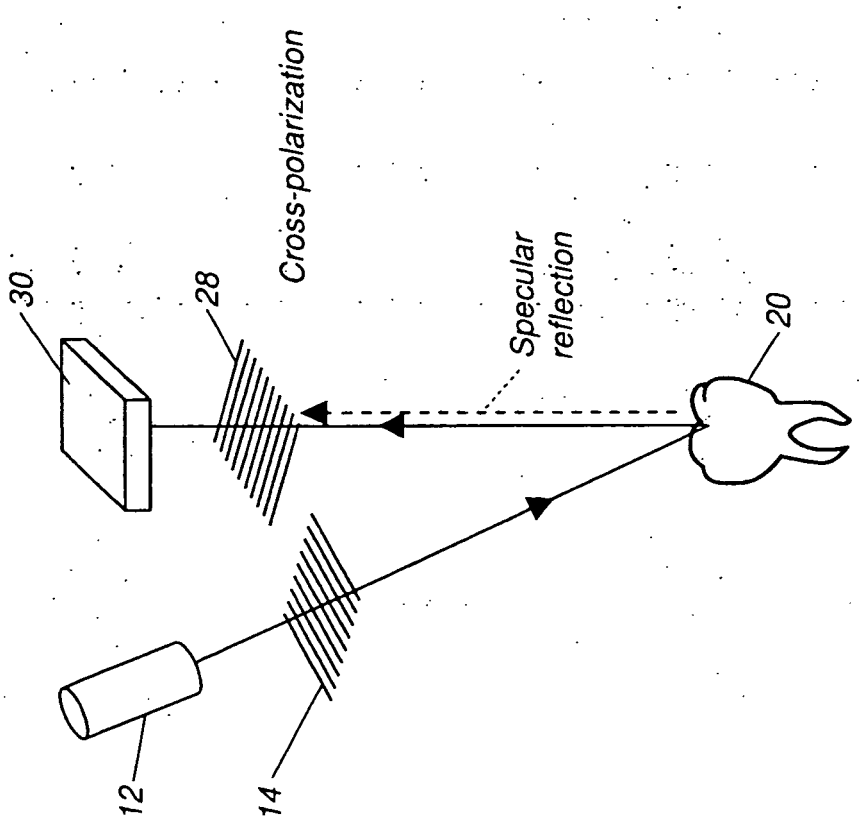


FIG. 2B

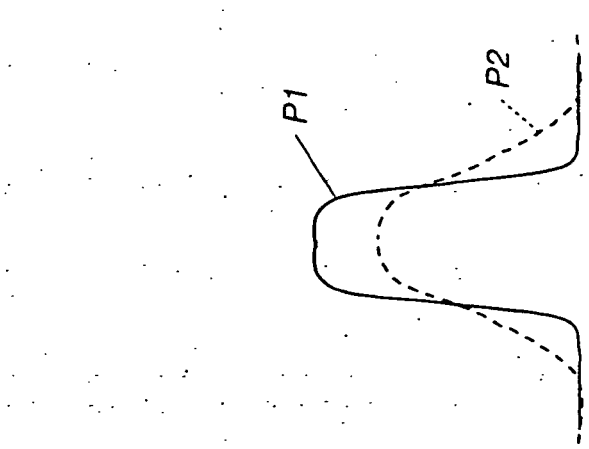


FIG. 3B

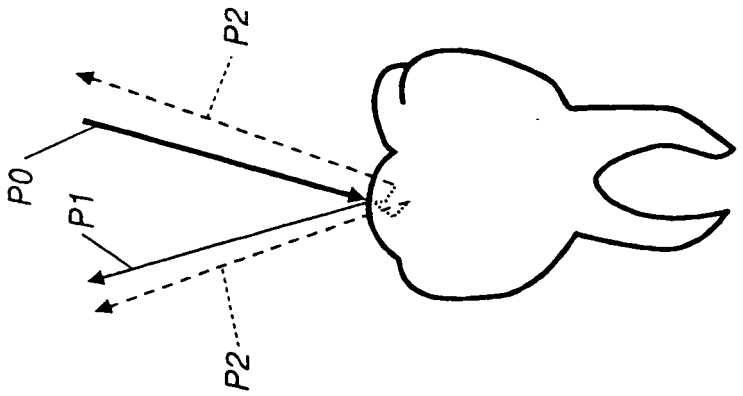


FIG. 3A

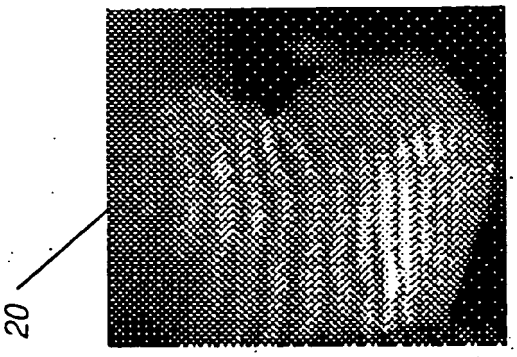


FIG. 4C

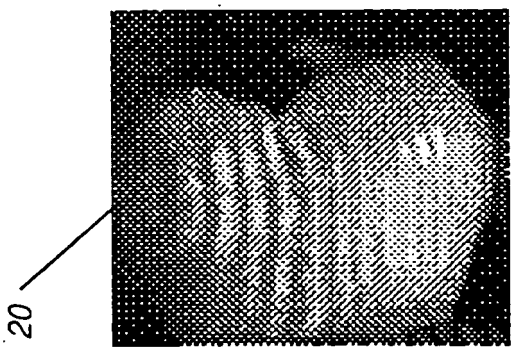


FIG. 4B

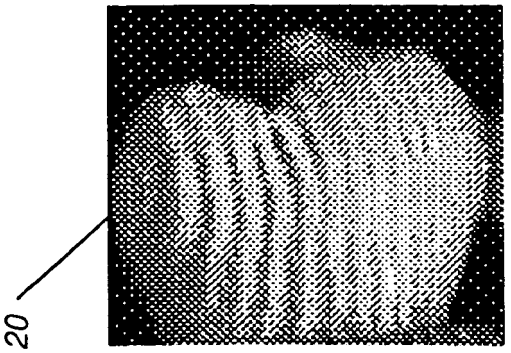


FIG. 4A

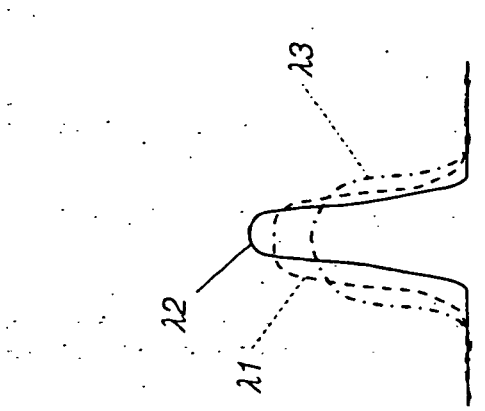


FIG. 5B

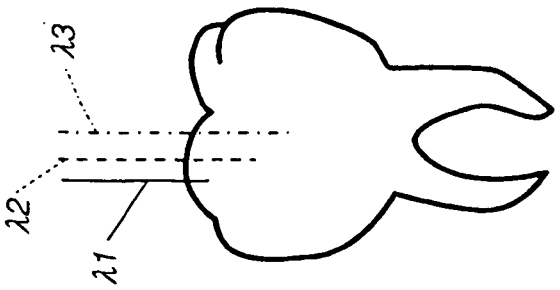


FIG. 5A

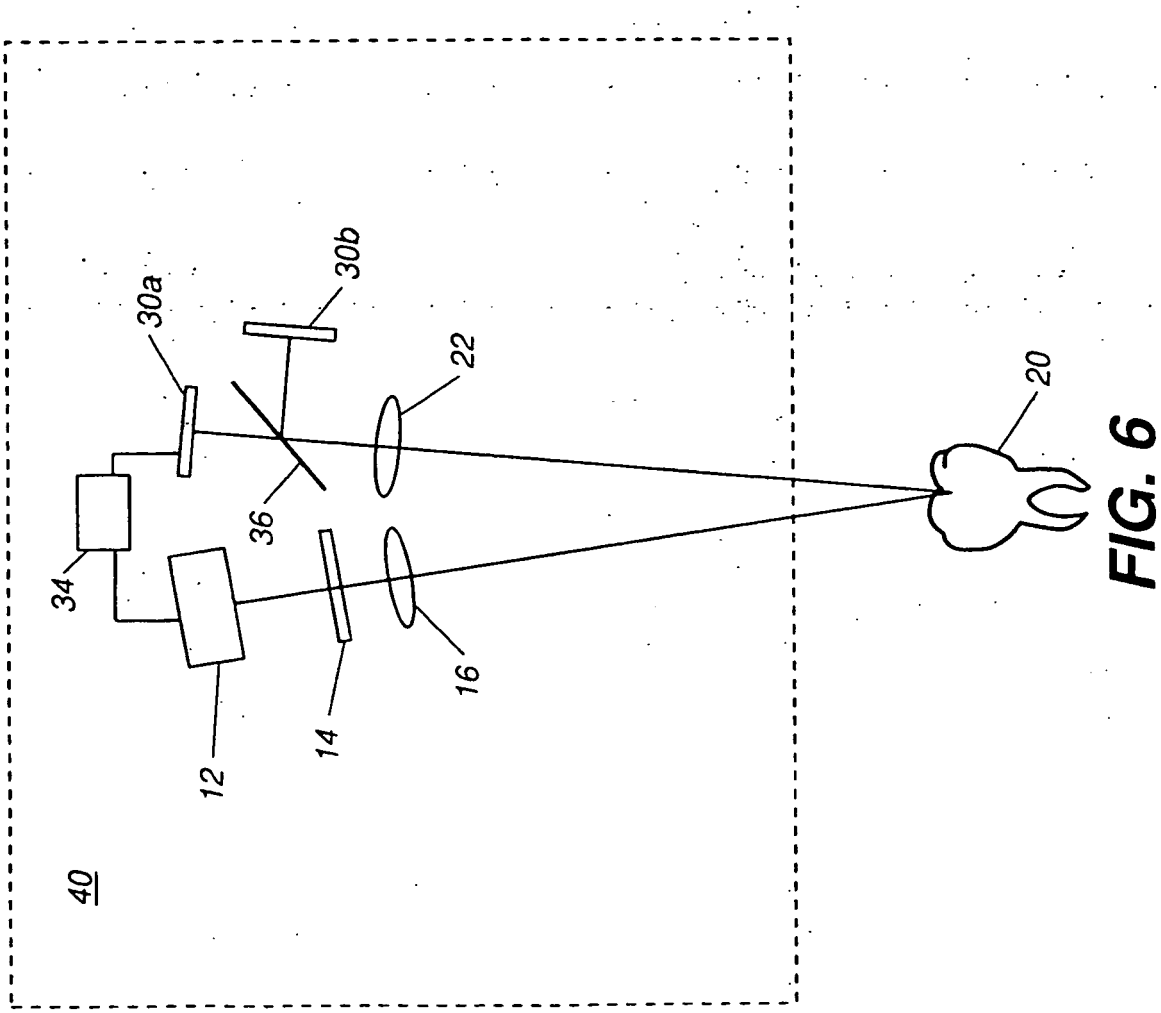


FIG. 6

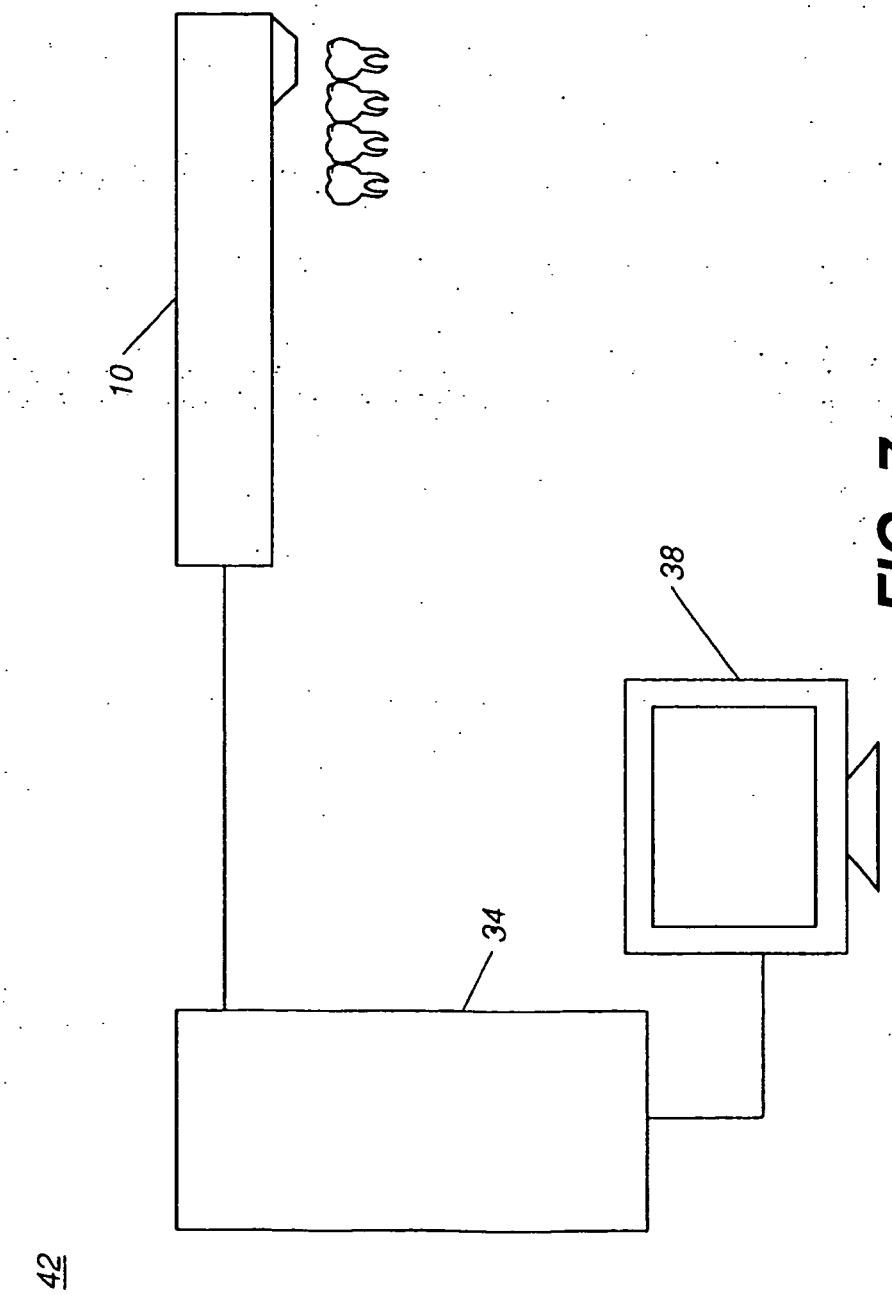


FIG. 7

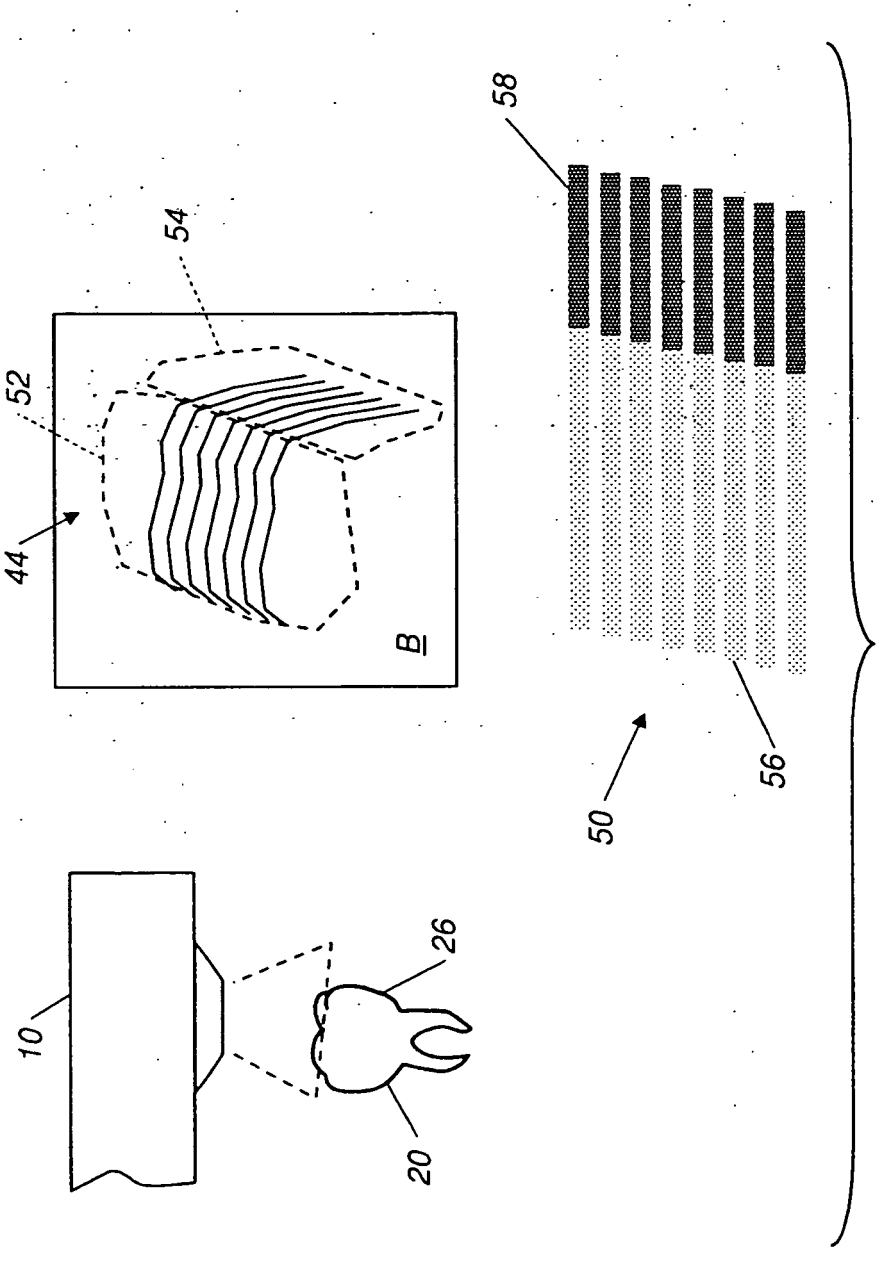


FIG. 8

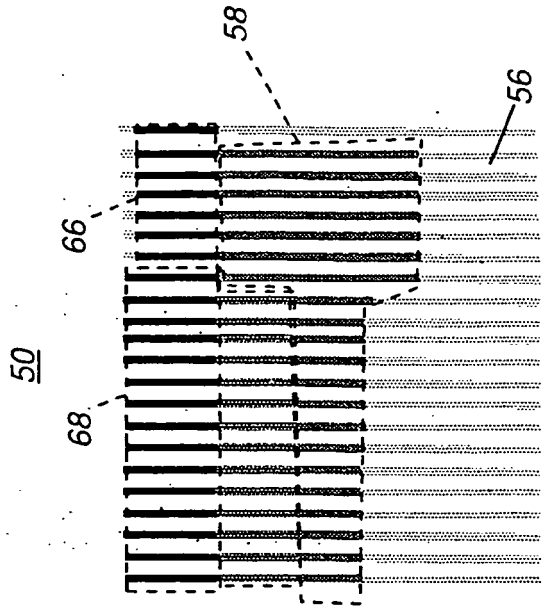


FIG. 9B

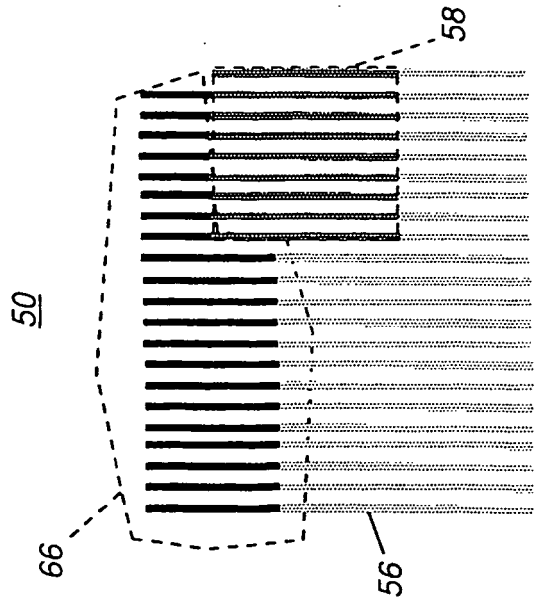


FIG. 9A

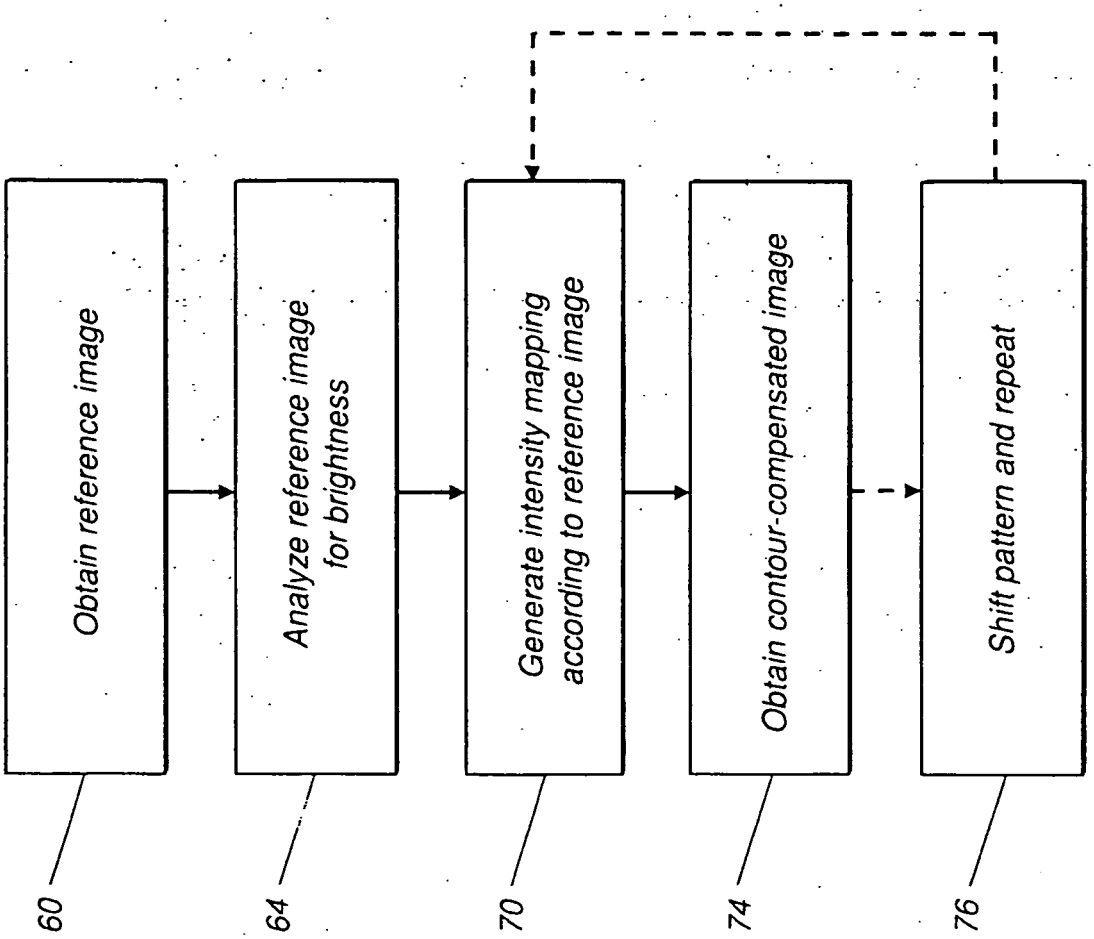

Obtain reference image
Analyze reference image for brightness
Generate intensity mapping according to reference image
Obtain contour-compensated image
Shift pattern and repeat
60
64
70
74
76

FIG. 10

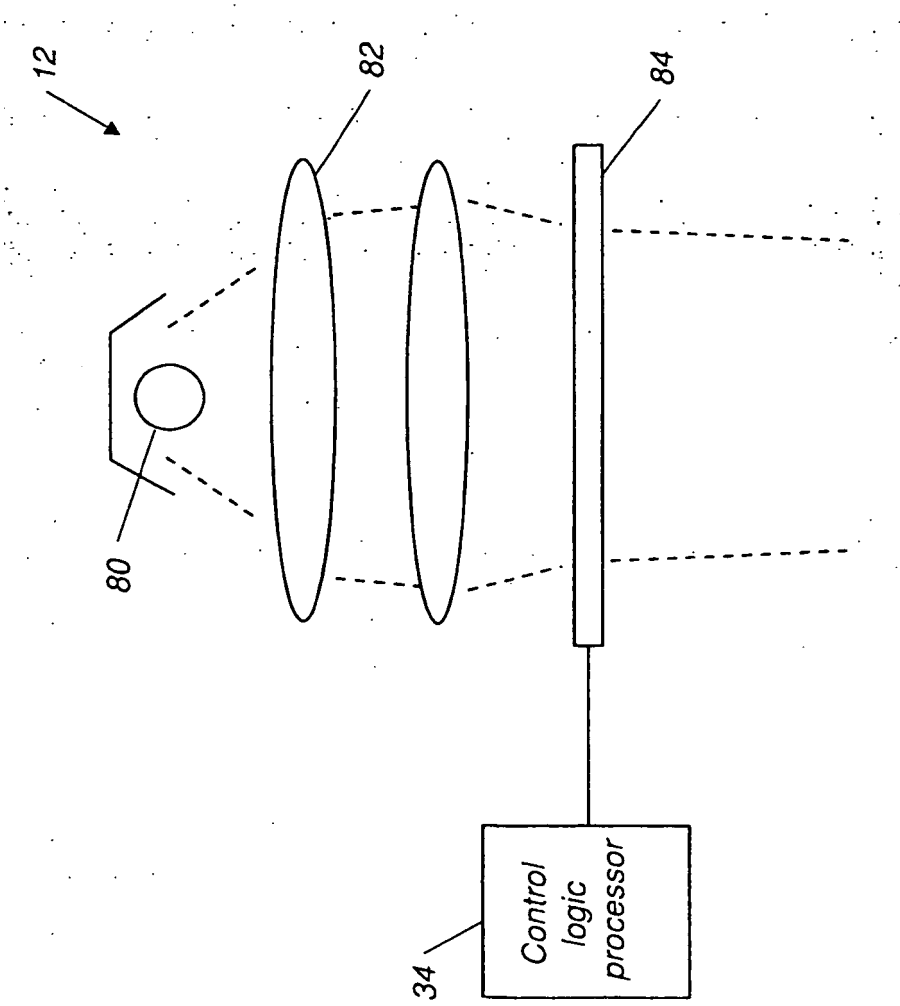


FIG. 11

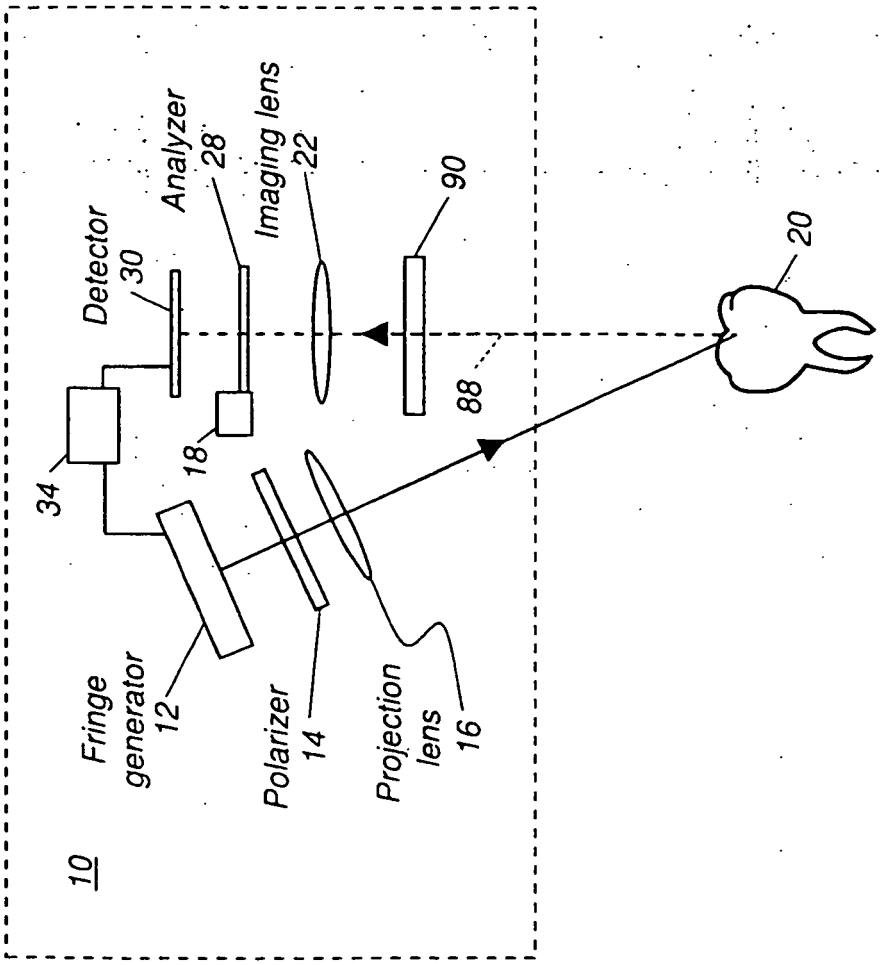

10
Fringe generator 12
Polarizer 14
Projection lens 16
18
34
Detector 30
Analyzer 28
Imaging lens 22
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88
20

FIG. 12

REFERENCES CITED IN THE DESCRIPTION

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